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Advances and challenges in water management within energy systems

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ABSTRACT

Energy systems face a growing vulnerability to the availability and quality of water sources as a consequence of rising energy demand and increasing climate variability. The vulnerability of energy systems to water utilization constraints could be mitigated by the effective design and implementation of water management strategies in energy conversion process and supply chain systems. Based on a broad literature review, this study provides a comprehensive examination of the recent advances in methodologies to support decision-making processes involving water management in the energy sector. Water management issues which require more attention by the research community, include: (i) development of decision-support models for biofuel supply chains that deal with water scarcity scenarios, (ii) integration of wastewater quality variability into the design and planning of water management strategies for the development of unconventional fossil fuels, (iii) improvements in the efficiency of cooling systems, and (iv) integration of decision-support tools with climate and weather models for the optimal design, planning, and operation of integrated water and energy supply chains, especially power systems. The systematic targeting of the aforementioned issues in the near future is critical and requires the joint efforts of the energy modeling as well as the weather and climate research communities, which to date have principally addressed water management issues from their own individual perspectives.

1. Introduction

Energy sources, including fossil fuels and renewable energy sources, have supported and will continue to support human prosperity across the globe. The International Energy Agency (IEA) systematically assesses and presents three different scenarios, i.e. *New Policies*, *Current Policies*, and *450* scenarios, to forecast global energy demand by 2040. The *450 scenario* refers to an energy pathway that curbs greenhouse gas emissions so that their atmospheric concentration does not exceeds 450 ppm of CO_2 in order to keep global warming below 2 °C. According to the projections of the IEA, in the *Current Policy*, *New Policy*, and *450* scenarios, world's primary energy demand is expected to growth by 45%, 32%, and 12% from 2013 to 2040, respectively. Likewise, global electricity demand is projected to increase over the same time period by 86%, 71% and 49%, for the same three scenarios, respectively [1]. However, the development of energy sources relies on water, which is subject to physical limitations and government regulations that can and do constraint its availability and accessibility.

As shown in Fig. 1, water is used in energy systems for the extraction, transportation, and processing of fossil energy sources, the irrigation of feedstock crops used to produce biofuels, as well as for power generation. Moreover, water of varying quality is also generated during the extraction of fossil and geothermal energy sources. As will be discussed in more detail in subsequent sections of this paper, the manner and extent to which water is utilized in energy systems is very technology and scenario specific and thus requires case by case analysis. However, on a macroscopic level, according to the IEA [2] in 2010 world's water withdrawal for the energy sector constituted 15% (~ 583 billion cubic meters (bcm)) of the total global water withdrawal, with the power sector accounting for roughly 90% of that share. Additionally, water consumption (here consumption is understood to be the portion of withdrawal that is not returned to the water source) for energy production was estimated to be about 11% (~ 66 bcm) of the water withdrawals for the energy sector. Water consumption in the energy sector is driven mostly by the production of fossil fuels, ethanol, and electricity from coal. For instance, the production of coal, oil and gas, ethanol, and electricity from coal, accounted for 11.9%, 39.6%, 14.8%, and 15.5% of the total water consumption for energy production in 2008 (~ 52 bcm), respectively [3]. It is noteworthy that global water consumption for ethanol production is comparable with that of electricity production from coal power plants and is higher than global water consumption for coal production, although the energy content of global ethanol production is roughly 1/100th that of global electricity production from coal power plants [3]. On a regional basis, the high

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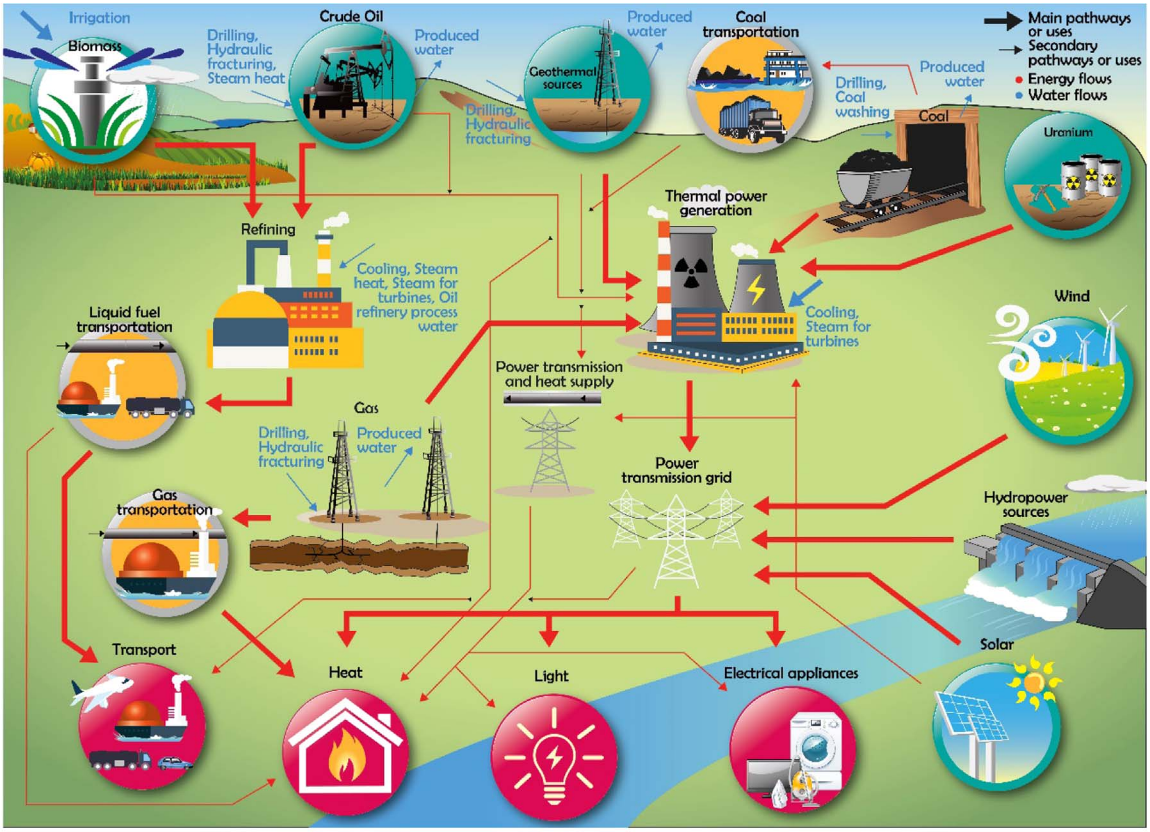

Fig. 1. Water use in energy systems. Arrows represent energy (red) and water (blue) flows. The thick and thin arrows denote main and secondary pathways or uses, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

energy consuming countries, the U.S. and BRIC (Brazil, Russia, India, and China) countries dominate the water consumption for the production of fuels and electricity [3]. However, the impacts of the water consumption of these countries is not confined within their boundaries. As shown in Ref. [4], while the gas and electricity sectors consume fresh water which originates mainly within the countries where the energy demand arises, the petroleum sector has a fresh water footprint that is largely international and thus impacts other regions as well. Clearly, the water-energy nexus ultimately has no geographic boundaries.

Under the *New Policy Scenario,* which constitutes the IEA baseline scenario, water withdrawals are estimated to increase by roughly 20% from 2010 to 2035. By contrast, water consumption is estimated to growth by 85% during the same time horizon. This remarkable increase in water consumption is driven by the expected expansion in the production of biofuels and implementation of technologies for energy efficiency improvements in the power sector (particularly in thermal power plants), which include innovation in the use of advanced cooling systems. Another metric of water utilization by energy systems is water intensity, which is defined as water utilization per unit of energy produced. It has been projected that, over the 2005–2090 period, the global water withdrawal intensity for electricity generation would likely decrease, while the water consumption intensity is expected to increase [5]. This trend in water intensity is expected to be driven by the ongoing shift from once-through to evaporative cooling systems in power plants and the expanded use of advanced power generation technologies.

It is evident that growth in demand for energy in various forms is directly constrained by water resources which are in limited supply and subject to variability. Thus, planning of energy system developments to meet the expected demand must be addressed in an integrated manner taking into account the technologies relevant to both energy production and water utilization. This paper seeks to provide a review of the current status of integrated water management strategies within the context of energy systems and suggest areas where advances in methodology are required. In the next section, we provide a global context for the water-energy nexus in term of national/regional energy demand and spatial distribution of water risk. In Section 3 we summarize the water intensity of different primary energy sources and power generation technologies. In Section 4 the decision elements associated with the water management in energy systems are discussed and the systems studies reported in the literature for primary energy and the power sector are reviewed. Finally, based on this literature review, in Section 5, the challenges and opportunities for advances in water management methodologies related to energy systems are identified.

2. Energy demand and water risk

Beyond the expected increase in water withdrawal and consumption for energy production discussed in the preceding section, various studies envisage important consequences on water availability due to increases in climate variability, including El Niño and La Niña abnormal weather patterns, in the coming decades [6–12]. For instance, rainfall shifts in tropical regions [6,12] along with increases in the frequency of El Niño and La Niña have been projected [10,11]. Additionally, it is expected that large CO_2 emission reduction targets in power systems would likely cause an increase in water demand for electricity generation, as would arise if coal generation is reduced in favour of nuclear power generation [13]. Furthermore, on a global scale, climate change mitigation policies are expected to decrease freshwater withdrawal and increase freshwater consumption in the energy sector [14,15]. Climate change is also expected to impact surface water quality, as a result of factors such as increased water temperature, toxic algal blooms, decline of dissolved oxygen levels, and increases in dissolved organic carbon [16]. Therefore, the worldwide vulnerability of energy systems to

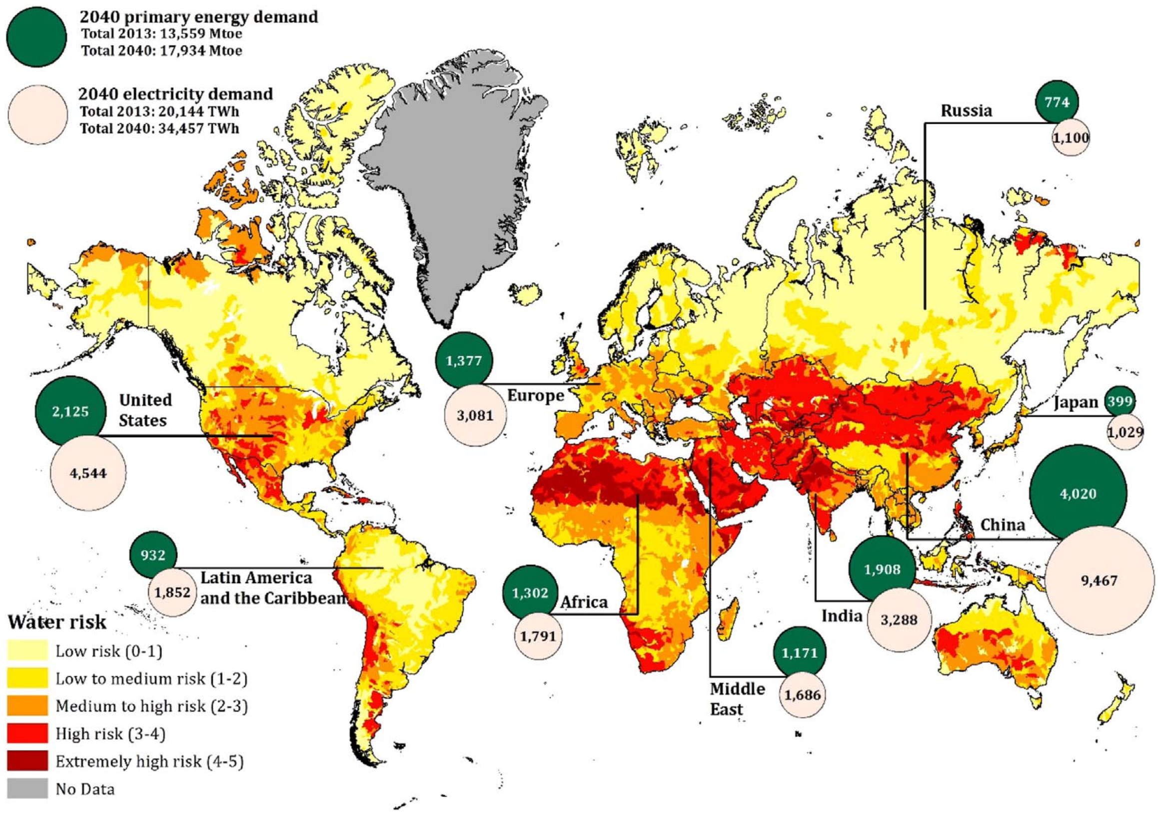

Fig. 2. Energy demand by 2040 [1] and 2014 water risk for different countries and regions [17]. Numbers inside the bubbles represent the numerical values of primary energy (green bubbles) or electricity (beige bubbles) demand by 2040; colours on the map represent spatial distribution of water risk (yellow indicates low water risk and maroon indicates extremely high water risk). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

availability and quality of water resources can be expected to be aggravated in the near future. Fig. 2 shows primary energy and electricity demand by 2040 and current (2014) water risk around the globe. Water risk is an aggregate qualitative measure of 12 indicators grouped into three categories: physical risk quantity, physical risk quality, and regulatory and reputational risk [17]. Primary energy demand will increase in all the regions except in U.S., Japan, and the European Union, while electricity demand is expected to grow in all of the regions. As is evident from Fig. 2, the Southwest of the U.S., North Africa, the Middle East, India and North China are regions wherein energy systems developments will be particularly impacted by water resource constraints. Consequently, the creation and implementation of decision-support tools to evaluate the impact of water management strategies on energy systems will play an increasingly important role not only in supporting the development of energy sources, but especially in the design, planning, and operation of integrated energy supply chains.

Even though the basic concepts of integrated water-energy system modeling, simulation, and optimization were established by the 1980s [18,19], the water-energy nexus has only been systematically addressed by the research community for the past two decades. Indeed, research studies on the water-energy nexus have undergone a rapid expansion in the last decade [20–25], including local [22] or regional/multi-regional [20,21,24] integrated water-energy systems in China [21,22], Middle East [20], and U.S. [23,24]. Detailed reviews of water-energy nexus approaches are reported in Refs. [26,27]. Specifically, the major challenges associated with the water-energy nexus include the appropriate modeling of the complexity and multidimensional nature of such integrated systems, spanning environmental, social, economic, technological, and political components [26]. Moreover, the need for decision-support frameworks with appropriate spatial and temporal resolutions has been recognized [27]. Additionally, the challenge of translating water-energy issues into local or regional political systems policy, governance, and regulations has been identified [27]. In the next sections we focus on specific cases of the water-energy nexus, including water intensity and water management strategies associated with the production and conversion of the principal energy sources.

3. Water intensity

In an energy and water demanding world, the quantification of the efficiency associated with the use of water to produce energy is undoubtedly an important aspect in evaluating energy sources and associated processing systems. For example, water intensity, defined as quantity of water utilized per unit of primary energy produced (gal/MMBtu), can be used to evaluate the merits of a given alternative fuel technology development. Additionally, water intensity can provide information about water use efficiency in energy conversion processes and technologies as well as energy supply chain systems. Water intensity is usually quantified via two distinct metrics: *water withdrawal* and *water consumption*. The former is used to denote the water volume taken from a surface or underground water source, i.e. the cool water pumped from a river or lake for cooling purposes in a thermal power plant. *Water consumption* pertains to the volume of water removed from a surface or underground water source that is not directly return to the source, i.e. the water evaporated in a cooling tower. Thus, water consumption is less than or equal to water withdrawal. Additionally, water consumption limits the water availability for supplying downstream demand, while water withdrawal impacts water quality of downstream users. A number of studies have addressed the quantification of water intensity for primary energy [28–38] and electricity generation [28,29,34,35,39–41].

3.1. Primary energy

As summarized in Fig. 1, water is used to produce both fossil (coal, gas and crude oil) and renewable, (bioethanol and biodiesel) primary energy sources. In the fuel cycle, which includes extraction (fossil fuels) or production of feedstock crops (biofuels), processing, and transportation, water is used for different purposes and at varying intensities. For instance, water is used in drilling and fracturing operations associated with the production of conventional and unconventional gas and crude oil. Additionally, in coal mines, water is used for drilling as well as for coal cutting and washing. In the case of biofuels, water is used extensively for the irrigation of feedstock crops for biomass production. However, no water is needed directly for the production of solar, wind, and geothermal energy sources. Water intensity for the extraction of fossil fuels varies from 0.6 to 15 gal/MMBtu, from 0.8 to 94 gal/MMBtu, and from 1 to 8 gal/MMBtu for shale gas, crude oil (conventional and enhanced oil recovery (EOR)), and coal, respectively [34,36,42]. As might be expected, water intensity for enhanced oil recovery is relatively high when compared with conventional oil. Moreover, water intensity for the extraction of conventional natural gas is close to zero [34,36]. By contrast, higher water intensities are associated with the production of feedstock crops for biofuel production. Specifically, water intensity for the production of corn and soybean ranges from 83 to 3805 gal/MMBtu and from 13,800 to 75,000 gal/MMBtu, respectively [34,36]. In general, water consumption for the transformation of fossil energy sources and the production of biofuels is lower than that for the extraction of fossil fuels or production of crops. For instance, water consumption for oil refining and for ethanol production ranges from 7 to 18 gal/MMBtu and from 13 to 14 gal/MMBtu, respectively [34,36]. A summary of ranges of water intensity for primary energy production, in terms of withdrawal and consumption, is shown in Fig. 3. It is evident that water intensity of biofuels production is generally higher than that of fossil fuels. Additionally, the wider ranges of the biofuel water intensities are due to variations in irrigation demand for different crops and regions. The high water intensities for biofuels are associated with the production of feedstock crops via irrigation, while the lower water intensities are associated with biofuels produced from feedstock crops that do not use irrigation and thus the water requirements are mostly for biomass processing. In general, unconventional fossil fuels are more water demanding than conventional fossil fuels due to the use of advanced technologies such as hydraulic fracturing, cyclic steam stimulation, and steam-assisted gravity drainage.

3.2. Power sector

Fossil–fired (coal and natural gas) and nuclear power plants are among the most demanding water users in the power sector. Moreover, the integration of carbon capture and sequestration (CCS) with coal power plants significantly increases the water intensity of coal power plants. Water withdrawal and consumption for electricity generation in thermal power plants are dominated by cooling needs during their operation [2,39,43]. Cooling systems for power plants can be classified as once-through and re-circulating, where re-circulating cooling systems can be subdivided into three subcategories: wet, dry, and hybrid [2]. Each cooling system alternative involves trade-offs associated with water withdrawal and consumption, effects on the quality of water sources, and impacts on the efficiency and cost of the power plants. For instance, the advantages of once-through cooling systems consist of lower water consumption as well as relatively low capital and operating costs. However, such systems have disadvantages in terms of environmental impact due to higher water withdrawals and the higher temperature of the downstream discharge, which can and does affect ecosystems and aquatic life [2,34]. On the other hand, dry cooling systems require near zero or minimal water withdrawal and consumption but do so at the expense of higher capital cost, lower plant efficiency (especially in hot climates), and large land area needs [2,34]. For example, water withdrawal and consumption for natural gas combined cycle power plants with once-through cooling systems ranges from 7500 to 20,000 gal/MWh and from 0 to 100 gal/MWh, respectively [39]. By contrast, both water withdrawal and consumption range from 0 to 4 gal/MWh for the same type of natural gas power plants but operating with dry cooling systems [39].

Hydropower plants are the biggest water users in power systems but most of the water used passes through turbines with minor water losses. Thus, water consumption for hydropower generation in power plants that rely upon stored water in reservoirs for power generation is mainly due to seepage and evaporation from reservoirs [2]. Average evaporative losses for hydropower plants in the U.S. is about 4500 gal/MWh [29]. By contrast, water intensity of renewable power generation technologies is much lower. Specifically, solar photovoltaic (PV) and wind (non-thermal renewables), use negligible amounts of water. Water uses for this type of technology are mostly associated with cleaning and washing panels [2,34,36]. However, water withdrawal and

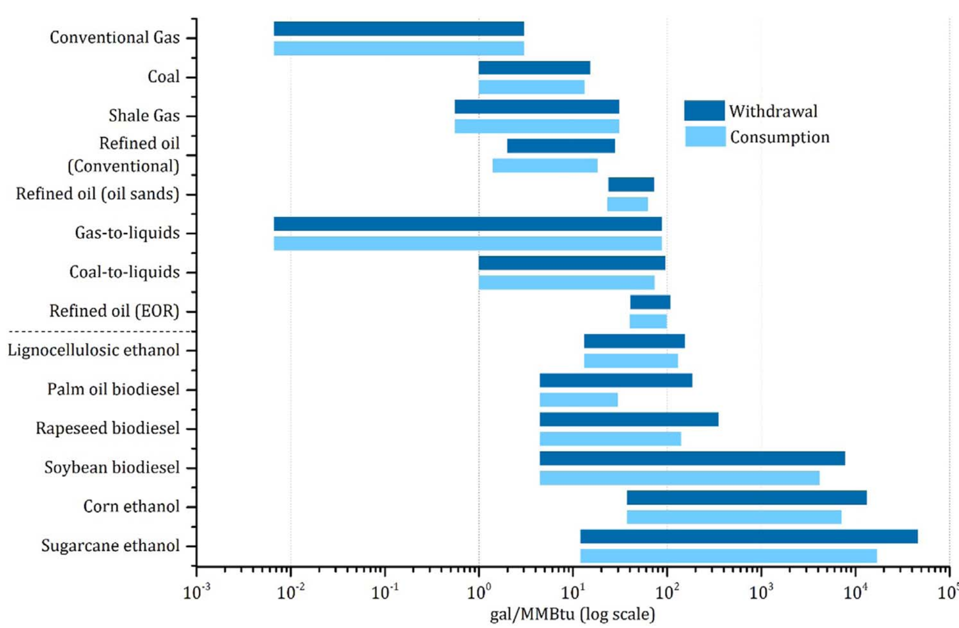

Fig. 3. Water intensity for primary energy production [2,28,29,41]. Horizontal bars represent ranges of water withdrawal intensity (dark blue bars) or water consumption intensity (light blue bars). Adapted with permission from IEA [2]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

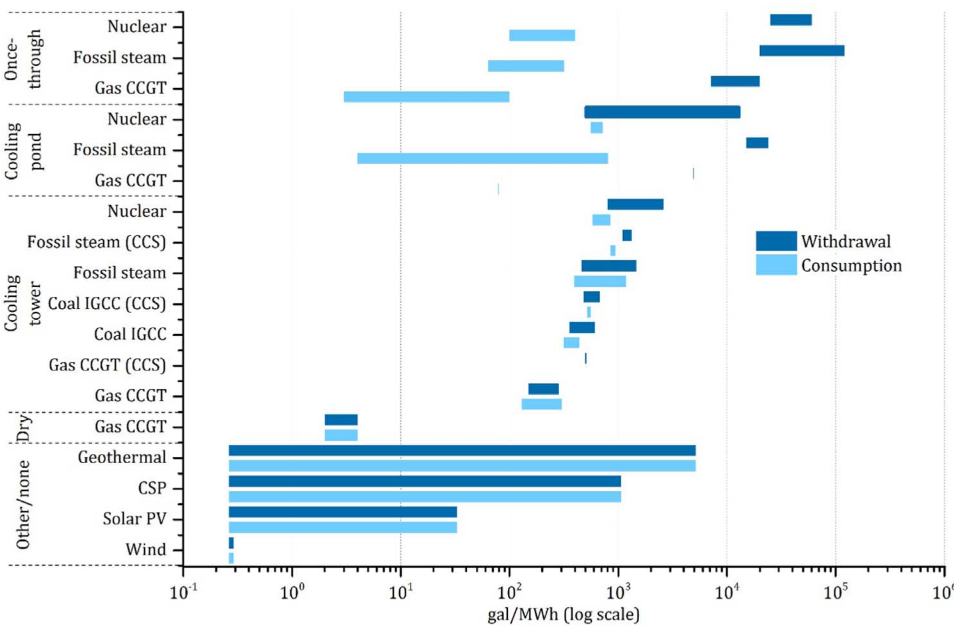

Fig. 4. Water intensity for power generation [2,39,45]. Horizontal bars represent ranges of water withdrawal intensity (dark blue bars) or water consumption intensity (light blue bars). Vertical texts in the vertical axis represent cooling technologies. Adapted with permission from IEA [2]. Abbreviations: CCGT, combined-cycle gas turbines; CCS, carbon capture and storage; IGCC, integrated gasification combined-cycle; CSP, concentrating solar power; PV, solar photovoltaic. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

consumption for thermal renewable power generation, i.e. geothermal and concentrating solar power (CSP), are generally higher when compared with the non-thermal technologies and vary significantly depending on the particular technology and cooling system used [2,34]. Specifically, water consumption for geothermal and CSP technologies ranges from 5 to 720 gal/MWh and from 4 to 1109 gal/MWh [39], respectively. An extensive review and harmonization of data associated with life cycle water withdrawal and consumption for electricity generation including fuel cycle, power plant cycle, and power plant operation can be found in Ref. [43]. A comprehensive summary of water intensity, based on withdrawal and consumption, for power generation technologies is given in Fig. 4. In general, non-thermal renewable power generation technologies, i.e. wind and solar PV, have lower water intensity than any other technology, while thermal power plants, which include geothermal, CSP, fossil, and nuclear, exhibit higher water intensities due to cooling needs. Water intensity of geothermal and CSP technologies varies widely depending on the power generation technology and the cooling system employed. Water intensity for thermal power generation varies based on the choice of cooling system technology. For instance, water withdrawals for power plants with once-through cooling systems are higher than those for power plants that employ cooling ponds, cooling towers, or dry cooling systems. However, a reverse trend is observed for water consumption intensity. Furthermore, water intensities for gas power plants with dry cooling systems are within the range of those of both non-thermal and thermal renewable power generation technologies. On a positive note, a recent study conducted on a regional U.S. power system demonstrated that the penetration of renewable energies could significantly reduce the water intensity of power generation [44].

4. Water management

Water management in energy systems encompasses the procurement, planning, development, distribution, and utilization of water resources in energy production and conversion processes as well as in energy supply chains. In this section, we briefly review the important decision elements that are part of any systems approach to water management, followed by a review of the extent and manner in which these elements have been addressed in systems studies involving primary energy production and power systems.

4.1. Decision elements

Systematic approaches for water management involve the following components: characterization of water resources, design of water distribution networks, design of water and wastewater treatment systems, and selection of cooling technologies. The first component consists of identifying the availability, expressed in terms of quantity and quality, and cost of water resources. The quantification of water availability must be based on information regarding downstream water demand and environmental flow requirements merged with hydrological balances, which include the forecast of precipitation, estimation of evapotranspiration, and the assessment of changes in groundwater and surface water storage. The accurate projection of rainfall conditions, specially over a long-term horizon, is still a challenging problem despite the decades long efforts of the weather and climate research community [46,47]. Moreover, the cost of water acquisition depends on access and usage charges imposed by state or country regulations. The design of water distribution networks involves the design of infrastructure, selection and sizing of transportation modes, and selection of water integration policies for water supply, considering water demand and quality requirements at each node as known parameters. The total cost, which is mostly associated with capital investments in water transportation infrastructure, is the most common economic performance metric used in formulating the water distribution problem [48,49]. The complexity of this problem increases with the number of water resources, demand nodes, and pollutants that are considered in the system.

Beyond the characterization of water resources and the design of water distribution networks, water and wastewater treatment systems are crucial for a better water use in production processes and systems, especially in primary energy conversion processes and supply chains. Water can be contaminated in energy systems by a variety of pollutants, including: inorganic, (heavy metals, sands, nitrates, chlorides, sulphates, and phosphates), organic (phenols, aromatic hydrocarbons, and methanol) and biological (bacteria, plankton, and fungi.) Alternative water treatment technologies, such as primary, secondary, tertiary treatments, are used for water source reduction, wastewater treatment, and reuse/recycle (reclamation) through the total or partial removal of the contaminants [50]. A summary of classification, applicability, suitability, and treatment cost for wastewater treatment technologies is provided in Fig. 5. For example, coagulation is classified as a primary

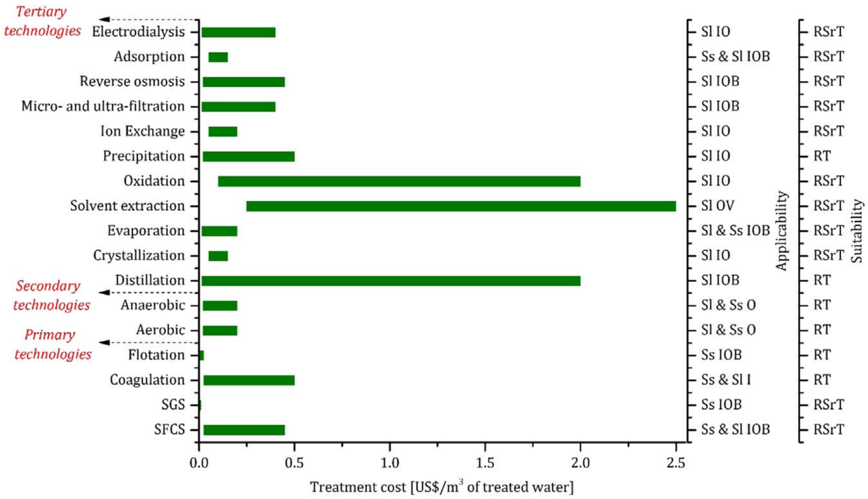

Fig. 5. Classification, applicability, suitability, and treatment cost for wastewater treatment technologies [50]. Horizontal bars represent ranges of treatment cost for technologies on the left vertical axis. The first and second right vertical axes represent the applicability and suitability of treatment technologies on the left vertical axis, respectively. Abbreviations: SFCS, screening, filtration and centrifugal separation; SGS, sedimentation and gravity separation; Sl, soluble; Ss, suspended; I, inorganics; O, organics; V, volatiles; B, biologicals; R, reclamation; T, treatment; Sr, source reduction.

treatment technology in which a coagulant, i.e. a chemical based either on aluminum or iron, is used to promote the settling of suspended and soluble inorganic pollutants that do not settle under conventional sedimentation and gravity schemes. This treatment technology is suitable for wastewater treatment and reclamation at a cost that ranges from 0.03 to 0.5 US$ per cubic meter of treated water. Primary treatments, which utilize physical and/or chemical processes, are used as a preliminary purification step. Then, secondary treatments (aerobic or anaerobic) can be performed to remove insoluble and soluble contaminants using biological methods, i.e. microbe based processes. After primary and secondary treatment, further removal of pollutants can be achieved by implementing tertiary treatment technologies, such as distillation, solvent extraction, and oxidation. These technologies are used to produce fresh water quality treated water. More detailed reviews of water treatment technologies, including individual processes, combined technologies, and perspectives on science and technology developments, are provided in Refs. [50–55]. The selection and configuration of treatment technologies for water and wastewater depends on many factors, including water or wastewater quality, environmental regulations, capital and operating costs of the treatment technologies, and water quality specifications for reuse/recycling. Therefore, effective water and wastewater treatment strategies usually require the use of decision-support tools, including models and mathematical programming techniques to arrive at optimal or at least good but sub-optimal decisions.

In addition to the water and wastewater treatment issues, water use for cooling is another important concern, particularly in the power sector. In thermal power plants, water is required for cooling exhaust steam from turbines. The water intensity, water withdrawal or consumption per electricity output, for cooling depends mainly on the technology employed by the cooling systems, i.e. once-through or recirculating. Moreover, every cooling system technology imposes energy penalties on electricity generation (% of power plant energy output consumed by the cooling system) and has a specific contribution to total capital cost of the plant. Low water withdrawal intensity in power plants usually implies a high energy penalty. Thus, the optimal design and operation of cooling systems for power plants must be aided by decision-support tools to effectively address the trade-offs that are involved. A brief comparison of advantages, disadvantages, and energy penalty levels for the most common cooling system technologies is provided in Table 1. As can be seen from the ranges of energy penalties, the details of implementation of cooling technologies can have a significant impact on the energy efficiency of the power plant and the integrated power system. Thus, these details must be part of any system-level study.

A wide range of studies have addressed the aforementioned decision

Table 1
Advantages, disadvantages, and energy penalty levels for cooling technologies in power generation [34,56].

Cooling system	Advantages	Disadvantages	Energy penalty [% of output]
Once-through	High cooling efficiency Low water consumption Mature technology	High water withdrawal Exposure to thermal discharge limits	0.7–2.3
Wet Towers/ Pond	Low water withdrawal Mature technology	High water consumption High capital cost	1.8–6.3
Dry	Minimal water withdrawal and consumption	High capital cost High energy penalty High land requirements	3.2–11.2
Hybrid	Lower capital cost than dry cooling Lower water consumption than wet tower/pond	Higher capital cost than wet tower/pond Limited technology experience	1.8–11.2

components of water management in the energy sector (See Table 2). Some of these studies have focused on the production, processing, and supply chain levels of primary energy, while others have concentrated on the power sector at both plant and system levels. A detailed review of these studies is presented in the next section.

4.2. Systems studies involving primary energy

A number of studies have been concentrated on the water management associated with primary energy production and processing [57,58,60–62,66–68]. Pioneering studies, published decades ago, addressed the optimal water allocation and minimization of wastewater in petroleum refinery operations including wastewater treatment to remove multiple contaminants [57,58]. For example, in a seminal study, an optimization model for the simultaneous optimization of water distribution and wastewater treatment in a petroleum refinery was developed [57]. This study reported more that 50% reduction in the total annual cost, which includes freshwater acquisition cost as well as investment and operating costs of wastewater treatment facilities, of the corresponding water management problem involving three contaminants. Additionally, the authors also reported a potential saving of ~ 24% in total fresh water demand. Another study reports similar potential fresh water savings for the optimal water distribution in refinery operations based on pinch analysis approaches and considered both single and multiple contaminant cases [58]. Additionally, it was

Table 2
Systematic approaches for water management in energy systems.

Energy systems		Decision elements				Ref.
		Water resources	Water distribution network	Water and wastewater treatment	Cooling system	
Primary energy	Production/Processing		☑	☑		[57–65][f]
			☑	☑	☑	[66,67][r], [68][h]
	Supply chain	☑				[69,70][r]
			☑			[71][h]
		☑	☑	☑		[72][f]
Power sector	Power plant				☑	[73–78]
		☑			☑	[79,80]
	Power system	☑				[81–84]
		☑			☑	[79,80,85–87]

Abbreviations: f, fossil; r, renewable; h, hybrid.

reported that the wastewater treatment for water recycling could reduce fresh water demand by ~ 47.5%, while lowering final wastewater flowrate by 58.3%. Several recent publications, while still concentrated on applications in petroleum refinery operations, pose the water management problem as a mixed-integer nonlinear programming problem (MINLP) which is solved using various mathematical decomposition and global optimization strategies [59,60]. By including retrofitting of existing infrastructure, it was reported that more than 10% reduction in fresh water consumption can be achieved [59]. In a further development along these lines, Koleva and coworkers [88] reported a general MINLP model for the optimal design of water and wastewater treatment problems. A notable features of this model is that it includes treatment of multiple pollutants and integrates primary, secondary, and tertiary treatment technologies.

The application of nonlinear programming (NLP) and MINLP optimization models for the minimization of water consumption in first- and second-generation bioethanol plants as well as in hybrid process that rely on biomass for the production of transportation fuels have also received attention in the literature [66–68]. For example, potential reductions of up to 87% in fresh water consumption for a first-generation corn based ethanol plant have been achieved using an NLP model to simultaneously optimize water distribution, wastewater treatment, and the configuration of the cooling system [66]. Furthermore, using a similar optimization approach, it was estimated that cooling water demand in thermo-chemical based second-generation bioethanol production process can be reduced by at least 30% through implementation of dry cooling systems [67]. In addition to these NLP models for water management in bioethanol production, an integrated MINLP model for the optimal water distribution, wastewater treatment, and cooling in a hybrid biomass, coal, and natural gas to liquid (CBGTL) process to produce transportation fuels has also been developed [68]. Potential fresh water savings of more than 50% were identified using the aforementioned MINLP model. Given the fact that water intensity in bioethanol and biodiesel plants is relatively low when compared with that of the production of the corresponding feedstock crops, a variety of studies have been devoted to address water issues in biofuels supply chains using mixed-integer linear programming (MILP) models [69–71,89]. Specifically, multi-objective MILP approaches have been proposed to optimize not only the economics but also the carbon and water footprints of corn- and stover-based bioethanol supply chains [69,70]. In these two studies, water stress index (WSI)- defined as a function of water withdrawal to water availability ratio- was considered as a metric for the quantification of the water stress associated with the bioethanol supply chain. Improvements in irrigation efficiency, i.e. using drip rather than sprinkle irrigation, were found to have a great impact on the water intensity of bioethanol. Another study developed an MILP model, incorporating freshwater allocation problem and optimized process configurations based on heat, power, and water integration, for a nationwide CBGTL supply chain [71].

Water-related issues associated with the development of shale gas resources have received increased attention even in the popular press. Shale plays rely on horizontal drilling and hydraulic fracturing techniques, which impose risks and impacts related to the depletion, degradation, and contamination of surface and underground water sources [90–95]. Accordingly, water management associated with the development of unconventional fossil fuels, in particular shale gas, has been subject of an intense research in recent years [61–65]. Most of these studies have been focused primarily on the water distribution and wastewater treatment subproblems, with little or no integration with the shale gas supply chain design and planning problem. For example, using either a mixed- integer linear fractional programming (MILFP) or an MINLP approach, it has been shown that it is feasible to achieve between 10.9% and 21% reduction in freshwater withdrawal by optimizing water distribution and wastewater treatment in the production of shale gas with fixed schedules of drilling and fracturing operations [62,63]. Additionally, uncertainty in water availability [61], water demand for fracturing operation and flow rate of flowback water [65], and the capacities of underground injection disposal sites and wastewater treatment plants [64] has also been evaluated. Recent studies have demonstrated that the design and planning of shale gas supply chains and the corresponding water management problem should be addressed in an integrated fashion given the actual synergies and tradeoffs associated with fresh water availability, wastewater quality, drilling schemes, and wastewater treatment strategies [72,96]. For example, variations in water availability could change significantly the optimal drilling scheme in term of well-pad configuration and schedule of drilling operations as well as the optimal supply chain infrastructure for the shale gas transportation and processing. Additionally, it has been shown that wastewater quality, i.e. total dissolved solids (TDS) concentration, can play an important role in the optimal development strategy for shale gas resources [97]. Indeed, the treatment of shale gas wastewater containing high TDS concentrations is technically challenging and expensive [98]. Therefore, the optimization under uncertainty in water management for shale gas development requires that more systematic, rather than subjective, ways be employed to identify the key uncertain parameters in the problem, for example, using global sensitivity analysis strategies [99,100]. Finally, different authors have provided broad reviews on the approaches for decision-making support in water management, which can be classified into mathematical programming, conceptual engineering, and pinch analysis approaches [101–103].

4.3. Systems studies involving the power sector

Water management in the power sector is a critical issue since, as noted previously, power generation technologies use water either for power generation or for cooling purposes. For instance, hydropower plants use potential and kinetic energy from dams and fast flowing streams or rivers, respectively. On the other hand, thermal power plants usually require considerable amounts of water for cooling in addition to

the water required to generate process steam to drive turbine-generator systems. Accordingly, the optimal design and operation of cooling systems in industrial processes and particularly in the power sector has received attention in the last two decades [73–77,104–107]. Conradie and Kröger [73] developed a mathematical simulation model for performance evaluation and design of a natural draft indirect dry cooling system. Based on this simulation model, up to 2.57% reduction in power generation cost was achieved using a sequential quadratic programming (SQP) approach to optimize both design and operating variables for the dry cooling system [74]. The inlet air temperature, in addition to ambient humidity and pressure, was shown to have a direct impact on the power output of gas turbines. For instance, a higher inlet air temperature significantly increase the energy penalty for gas power plants with dry cooling systems. Specifically, it is estimated that power output is reduced between 5% and 10% of the international organization for standards (ISO)-rated power output (ambient temperature of 15 °C) for every 10 °C increase in inlet air temperature [105]. Thus, turbine inlet air cooling technologies, i.e. fogging systems, evaporative coolers, and absorption chillers [108–110], to curb the energy penalty of high inlet air temperature are desirable for gas turbines located in hot regions or operated during hot seasons. Accordingly, the effects of inlet ambient air temperature on dry cooling systems have also been studied [76,77,105]. It was reported, based on an analytical model, that inlet fogging is preferable, in term of power efficiency, when ambient temperature is between 15 °C and 20 °C. Inlet chilling is desirable when ambient temperature and relative humidity are greater than 25 °C and 0.4, respectively [76]. Other authors have focused on the optimal design and operation of wet cooling systems [75,104,106], wherein the recirculation water flow rate and the water return temperature were found to be the most important decision variables. However, it has been shown that the improvement associated with the optimization of radial fill profiles and layouts of water flows across the cooling tower are marginal [75]. Moreover, an MINLP model for the synthesis of a system of re-circulating cooling towers has also been developed [107]. It was demonstrated (using the previous MINLP model) that a multiple cooling towers configuration with different supply temperatures performs better than traditional systems, which consist of a single cooling tower. A stochastic optimization framework was also developed for the optimal operation of thermal power plants (focused on the cooling system) with constraints in water intake and uncertain weather conditions [78]. Variations between 5–10% in the maximum capacity of a pulverized coal power plant were estimated as a result of daily fluctuations in weather conditions.

As described previously, the power sector is particularly vulnerable to water sources and climate change. For instance, over the 2040–2069 time horizon, reductions in usable power generation capacity for more than 61% and 81% of worldwide hydropower and thermoelectric power plants respectively, have been estimated [87]. Additionally, reductions ranging from 7.2% to 8.8% for vulnerable power stations ($\sim$ 46% of total existing capacity) in the Western United States considering a ten-year drought were also predicted [86]. It has also been found that the cooling system plays an important role in the adaptability of thermal power plants to climate change [80], while, of course, hydropower plants are quite vulnerable to declining water inflows. Indeed, using the 2005–2030 time frame, it was illustrated that water demand for power generation in U.S. can be reduced by up to 30%, through the change or reconfiguration of cooling systems [111]. At a regional scale, a shift from open-loop to closed-loop cooling systems in the State of Illinois, could decrease water withdrawals by $\sim$ 96% ($\sim$ 21 bcm/yr), while increasing water consumption by $\sim$ 58% ($\sim$ 0.18 bcm/yr) [112]. Therefore, decision-support tools for the design, planning, and operation of power plants and power systems that rely primarily on thermal generation or hydroelectricity are the key for the adaptation of the power sector to constraints on water resources and CO_2 emissions as well to climate change [79,81,82,113,114]. Koch and Vögele [79] developed a water management model for a system of thermal power plants, considering water demand forecast, future water availability, water shortages, and water temperature. This study reports that, assuming a 2.1 °C of temperature increase by 2050, climate warming could increase water demand up to 30% for power generation plants in Germany. Moreover, an NLP model was developed for the optimal operation of large-scale hydropower systems, i.e. from 2.3 GW to 69.4 GW of installed capacity, based on monthly inflow forecasts over a 5-year operation window [81]. This study reports that, using historical operational data as reference, the NLP model provides solutions that represent improvements between 4.1% and 6.9% in the total energy production of the hydropower systems. Recently, Guerra et al. [113] developed an integrated framework for the simultaneous design and planning of generation and transmission expansion in power systems. The framework, which is based on MILP models for both *business as usual* and *CO_2 mitigation policy* scenarios, was applied to an interconnected power system where hydropower plants account for roughly 70% of the total installed capacity. It was shown that high CO_2 emission reduction targets for such system can be achieved by simultaneously integrating renewable generation, i.e. wind and geothermal power sources, and increasing hydropower generation capacity, which allow the reduction of CO_2 emissions without affecting the reliability of the system. Uncertainty have also been considered in the planning of hydropower systems [83,84]. For instance, a risk management approach was used for the optimal scheduling and contract management of a hydropower system considering uncertainty in both inflow and spot market prices of electricity [83]. Moreover, general circulation models (GCMs) were used to generate climate change scenarios that are integrated into a stochastic dynamic programming (SDP) approach to provide optimal monthly operating policies for a multiuse reservoir serving irrigation, flood control, and power generation [84].

5. Challenges and opportunities

Worldwide energy systems, which encompass water demanding processes and systems, have and will continue to face vulnerability due to availability and quality of water sources. This vulnerability will undoubtedly increase in the near future as a consequence of the rising energy demand and the intensification of climate variability. Adaptation strategies include, among others, the strategic selection of less water intensive energy sources and technologies, efficiency improvement in energy conversion processes and systems, and the reduction of fresh water consumption by increasing water reuse and recycle within energy systems. An effective water management strategy certainly would diminish the vulnerability of energy systems to this key resource. However, water management involves complex decision problems that must include the systematic assessment of different fresh water source alternatives, water and wastewater treatment technologies, cooling technologies, and water integration strategies, while considering quality and availability of water resources, environmental constraints regarding water withdrawal and discharge, and specifications on water requirements within the energy processes and systems.

Although the research community has devoted significant attention to water management problems to date, there are still challenges and opportunities in the energy sector to be addressed. Specifically, the development of high fidelity optimization tools for biofuel supply chains that feature appropriate granularity and accuracy of process models, while including constraints on water uses for the production of feedstock crops, is a research area that requires more attention. Also, the design of biofuel supply chains based on feedstock crops that rely essentially upon natural precipitations rather than on irrigation is a topic that should be addressed. Similarly, the main challenge associated with water management in unconventional fossil fuel supply chains derives from addressing spatial and temporal variations in wastewater quality, i.e. total dissolved solid and total suspended solids. In the area of power generation, the optimal design and operation of dry and hybrid cooling systems to mitigate the high capital costs and energy

penalties is a topic that will gain importance in the next decades. The effective development, implementation, and operation of such cooling systems could alleviate the vulnerability of power systems to the increasing climate variability. Moreover, the integration of climate and weather models with decision-support tools for both the optimal long-term and short-term design, planning, and operation of integrated water and energy supply chains is an open research area that requires the effective collaboration between the weather and climate modeling and energy modeling research communities. However, since it seems that interdisciplinary research projects are less successful at receiving support when compared with those that have a narrower focus [115], funding may constitutes one of the major barriers for the development of robust and effective water management strategies in energy systems.

Finally, there are computing technology related issues that need attention. The development of these kind of integrated decision-support tools imposes challenges, from the computational point of view, in terms of high variable dimensionality as well as model scale and non-linearity. To tackle decision problems of realistic scale, the development and implementation of problem decomposition and parallelization approaches need to be investigated. Additionally, access to these decision support tools and their outputs by non-specialists should be facilitated via design and implementation of appropriate human-machine interfaces and data visualization tools.

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References

[1] International Energy Agency. World energy outlook; 2015. ⟨http://dx.doi.org/10.1787/weo-2015-en⟩.
[2] International Energy Agency. Water for energy: is energy becoming a thirstier resource? World energy outlook; 2012. p. 1–33.
[3] Spang ES, Moomaw WR, Gallagher KS, Kirshen PH, Marks DH. The water consumption of energy production: an international comparison. Environ Res Lett 2014;9:105002. http://dx.doi.org/10.1088/1748-9326/9/10/105002.
[4] Holland RA, Scott KA, Flörke M, Brown G, Ewers RM, Farmer E, et al. Global impacts of energy demand on the freshwater resources of nations. Proc Natl Acad Sci USA 2015;112:E6707–16. http://dx.doi.org/10.1073/pnas.1507701112.
[5] Davies EGR, Kyle P, Edmonds JA. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv Water Resour 2013;52:296–313. http://dx.doi.org/10.1016/j.advwatres.2012.11.020.
[6] Neelin JD, Münnich M, Su H, Meyerson JE, Holloway CE. Tropical drying trends in global warming models and observations. Proc Natl Acad Sci USA 2006;103:6110–5. http://dx.doi.org/10.1073/pnas.0601798103.
[7] Allan RP, Soden BJ. Atmospheric warming and the amplification of precipitation extremes. Science (80-) 2008;321:1481–4. http://dx.doi.org/10.1126/science.1160787.
[8] Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, et al. Stationarity is dead: whither water management? Science (80-) 2008;319:573–4. http://dx.doi.org/10.1126/science.1151915.
[9] Dai A. Drought under global warming: a review. Wiley Interdiscip Rev Clim Change 2011;2:45–65. http://dx.doi.org/10.1002/wcc.81.
[10] Cai W, Borlace S, Lengaigne M, van Rensch P, Collins M, Vecchi G, et al. Increasing frequency of extreme El Niño events due to greenhouse warming. Nat Clim Change 2014;5:1–6. http://dx.doi.org/10.1038/nclimate2100.
[11] Cai W, Wang G, Santoso A, McPhaden MJ, Wu L, Jin F-F, et al. Increased frequency of extreme La Niña events under greenhouse warming. Nat Clim Change 2015;5:132–7. http://dx.doi.org/10.1038/nclimate2492.
[12] Chadwick R, Good P, Martin G, Rowell DP. Large rainfall changes consistently projected over substantial areas of tropical land. Nat Clim Change 2015:1–6. http://dx.doi.org/10.1038/nclimate2805.
[13] Webster M, Donohoo P, Palmintier B. Water–CO_2 trade-offs in electricity generation planning. Nat Clim Change 2013;3:1029–32. http://dx.doi.org/10.1038/nclimate2032.
[14] Fricko O, Parkinson SC, Johnson N, Strubegger M, Vliet MT, van, Riahi K. Energy sector water use implications of a 2 °C climate policy. Environ Res Lett 2016;11:034011. http://dx.doi.org/10.1088/1748-9326/11/3/034011.
[15] Kyle P, Davies EGR, Dooley JJ, Smith SJ, Clarke LE, Edmonds JA, et al. Influence of climate change mitigation technology on global demands of water for electricity generation. Int J Greenh Gas Control 2013;13:112–23. http://dx.doi.org/10.1016/j.ijggc.2012.12.006.
[16] Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade AJ. A review of the potential impacts of climate change on surface water quality. Hydrol Sci J 2009;54:101–23. http://dx.doi.org/10.1623/hysj.54.1.101.
[17] World Resources Institute (WRI). Water risk atlas; 2014. ⟨http://www.wri.org/applications/maps/aqueduct-atlas/#x=8.00&y=0.25&s=ws!20!28!c&t=waterrisk&w=def&g=0&i=BWS-16!WSV-16!SV-2!HFO-4!DRO-4!STOR-8!GW-8!WRI-4!ECOS-2!MC-4!WCG-8!ECOV-2&tr=ind-1!prj-1&l=3&b=terrain&m=group⟩. [Accessed 17 May 2016].
[18] Buras N. Determining the feasibility of incorporating water resource constraints into energy models. Final Rep Stanford Univ, CA Dept Oper Res; 1979.
[19] Lall U, Mays LW. Model for planning water-energy systems. Water Resour Res 1981;17:853–65. http://dx.doi.org/10.1029/WR017i004p00853.
[20] Dubreuil A, Assoumou E, Bouckaert S, Selosse S, Maïzi N. Water modeling in an energy optimization framework – the water-scarce middle east context. Appl Energy 2013;101:268–79. http://dx.doi.org/10.1016/j.apenergy.2012.06.032.
[21] Wang S, Chen B. Energy–water nexus of urban agglomeration based on multi-regional input–output tables and ecological network analysis: a case study of the Beijing–Tianjin–Hebei region. Appl Energy 2016;178:773–83. http://dx.doi.org/10.1016/j.apenergy.2016.06.112.
[22] Fang D, Chen B. Linkage analysis for the water–energy nexus of city. Appl Energy 2017;189:770–9. http://dx.doi.org/10.1016/j.apenergy.2016.04.020.
[23] U.S. Department of Energy. The water-energy nexus: challenges and opportunities; 2014. ⟨http://dx.doi.org/10.1007/s13398-014-0173-7.2⟩.
[24] Ackerman F, Fisher J. Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States. Energy Policy 2013;59:235–41. http://dx.doi.org/10.1016/j.enpol.2013.03.027.
[25] Hussey K, Pittock J. The energy–water nexus: managing the links between energy and water for a sustainable future. Ecol Soc 2012;17:art31. http://dx.doi.org/10.5751/ES-04641-170131.
[26] Hamiche AM, Stambouli AB, Flazi S. A review of the water-energy nexus. Renew Sustain Energy Rev 2016;65:319–31. http://dx.doi.org/10.1016/j.rser.2016.07.020.
[27] Khan Z, Linares P, García-González J. Integrating water and energy models for policy driven applications. A review of contemporary work and recommendations for future developments. Renew Sustain Energy Rev 2017;67:1123–38. http://dx.doi.org/10.1016/j.rser.2016.08.043.
[28] Gleick P. Water and energy. Annu Rev Energy Environ 1994;19:267–99.
[29] U.S. Department of Energy. Energy demands on water resources: Report to congress on the interdependencies of energy and water; 2006.
[30] King CW, Webber ME. Water intensity of transportation. Environ Sci Technol 2008;42:7866–72. http://dx.doi.org/10.1021/es800367m.
[31] Gerbens-Leenes W, Hoekstra AY, van der Meer TH. The water footprint of bioenergy. Proc Natl Acad Sci USA 2009;106:10219–23. http://dx.doi.org/10.1073/pnas.0812619106.
[32] Dominguez-Faus R, Powers SE, Burken JG, Alvarez PJ. The water footprint of biofuels: a drink or drive issue? Environ Sci Technol 2009;43:3005–10. http://dx.doi.org/10.1021/es802162x.
[33] Fargione JE, Plevin RJ, Hill JD. The ecological impact of biofuels. Annu Rev Ecol Evol Syst 2010;41:351–77. http://dx.doi.org/10.1146/annurev-ecolsys-102209-144720.
[34] Mielke E, Diaz Anadon L, Narayanamurti V. Water consumption of energy resource extraction, processing, and conversion; 2010. doi:Discussion Paper No. 2010–2015.
[35] Mulder K, Hagens N, Fisher B. Burning water: a comparative analysis of the energy return on water invested. Ambio 2010;39:30–9. http://dx.doi.org/10.1007/s13280-009-0003-x.
[36] McMahon JE, Price SK. Water and energy interactions. Annu Rev Environ Resour 2011;36:163–91. http://dx.doi.org/10.1146/annurev-environ-061110-103827.
[37] Fazio S, Monti A. Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass- Bioenergy 2011;35:4868–78. http://dx.doi.org/10.1016/j.biombioe.2011.10.014.
[38] Clark CE, Horner RM, Harto CB. Life cycle water consumption for shale gas and conventional natural gas. Environ Sci Technol 2013;47:11829–36. http://dx.doi.org/10.1021/es4013855.
[39] Macknick J, Newmark R, Heath G, Hallett KC. A review of operational water consumption and withdrawal factors for electricity generating technologies; 2011. ⟨http://dx.doi.org/10.1088/1748-9326/7/4/045802⟩.
[40] Macknick J, Newmark R, Heath G, Hallett KC. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett 2012;7:045802. http://dx.doi.org/10.1088/1748-9326/7/4/045802.
[41] Schornagel J, Niele F, Worrell E, Böggemann M. Water accounting for (agro)industrial operations and its application to energy pathways. Resour Conserv Recycl 2012;61:1–15. http://dx.doi.org/10.1016/j.resconrec.2011.12.011.
[42] Yergin D, Frei C. Thirsty energy: water and energy in the 21st century; 2008.
[43] Meldrum J, Nettles-Anderson S, Heath G, Macknick J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ Res Lett 2013;8:1458–60. http://dx.doi.org/10.1088/1748-9326/8/1/015031.
[44] Peck JJ, Smith AD. Quantification and regional comparison of water use for power

generation: a California ISO case study. Energy Rep 2017;3:22–8. http://dx.doi.org/10.1016/j.egyr.2016.11.002.
[45] U.S. Department of Energy. Estimating freshwater needs to meet future thermoelectric generation requirements. US Dep Energy/National Energy Technol Lab; 2011.
[46] Kent C, Chadwick R, Rowell DP. Understanding uncertainties in future projections of seasonal tropical precipitation. J Clim 2015;28:4390–413. http://dx.doi.org/10.1175/JCLI-D-14-00613.1.
[47] Bauer P, Thorpe A, Brunet G. The quiet revolution of numerical weather prediction. Nature 2015;525:47–55. http://dx.doi.org/10.1038/nature14956.
[48] Eusuff M, Lansey K. Optimization of water distribution network design using the shuffled frog leaping algorithm. J Water Resour Plan Manag 2003;129:210–25. http://dx.doi.org/10.1061/(ASCE)0733-9496(2003)129:3(210).
[49] Gunaratnam M, Alva-Argáez A, Kokossis A, Kim J-K, Smith R. Automated design of total water systems. Ind Eng Chem Res 2005;44:588–99. http://dx.doi.org/10.1021/ie040092r.
[50] Gupta VK, Ali I, Saleh TA, Nayak A, Agarwal S. Chemical treatment technologies for waste-water recycling – an overview. RSC Adv 2012;2:6380. http://dx.doi.org/10.1039/c2ra20340e.
[51] Gogate PR, Pandit AB. A review of imperative technologies for wastewater treatment I: oxidation technologies at ambient conditions. Adv Environ Res 2004;8:501–51. http://dx.doi.org/10.1016/S1093-0191(03)00032-7.
[52] Gogate PR, Pandit AB. A review of imperative technologies for wastewater treatment II: hybrid methods. Adv Environ Res 2004;8:553–97. http://dx.doi.org/10.1016/S1093-0191(03)00031-5.
[53] Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Mariñas BJ, Mayes AM. Science and technology for water purification in the coming decades. Nature 2008;452:301–10. http://dx.doi.org/10.1038/nature06599.
[54] Striolo A, Michaelides A, Joly L. The carbon-water interface: modeling challenges and opportunities for the water-energy nexus. Annu Rev Chem Biomol Eng 2016;7:533–56. http://dx.doi.org/10.1146/annurev-chembioeng-080615-034455.
[55] Wade Miller G. Integrated concepts in water reuse: managing global water needs. Desalination 2006;187:65–75. http://dx.doi.org/10.1016/j.desal.2005.04.068.
[56] Byers EA, Hall JW, Amezaga JM. Electricity generation and cooling water use: UK pathways to 2050. Glob Environ Chang 2014;25:16–30. http://dx.doi.org/10.1016/j.gloenvcha.2014.01.005.
[57] Takama N, Kuriyama T, Shiroko K, Umeda T. Optimal water allocation in a petroleum refinery. Comput Chem Eng 1980;4:251–8. http://dx.doi.org/10.1016/0098-1354(80)85005-8.
[58] Wang YP, Smith R. Wastewater minimisation. Chem Eng Sci 1994;49:981–1006. http://dx.doi.org/10.1016/0009-2509(94)80006-5.
[59] Alva-Argáez A, Kokossis AC, Smith R. The design of water-using systems in petroleum refining using a water-pinch decomposition. Chem Eng J 2007;128:33–46. http://dx.doi.org/10.1016/j.cej.2006.10.001.
[60] Faria DC, Bagajewicz MJ. Global optimization of water management problems using linear relaxation and bound contraction methods. Ind Eng Chem Res 2011. http://dx.doi.org/10.1021/ie101206c. [110207125802096].
[61] Yang L, Grossmann IE, Manno J. Optimization models for shale gas water management. AIChE J 2014;60:3490–501. http://dx.doi.org/10.1002/aic.14526.
[62] Gao J, You F. Optimal design and operations of supply chain networks for water management in shale gas production: MILFP model and algorithms for the water-energy nexus. AIChE J 2015;61:1184–208. http://dx.doi.org/10.1002/aic.14705.
[63] Lira-Barragán LF, Ponce-Ortega JM, Serna-González M, El-Halwagi MM. Optimal reuse of flowback wastewater in hydraulic fracturing including seasonal and environmental constraints. AIChE J 2016;62:1634–45. http://dx.doi.org/10.1002/aic.15167.
[64] Zhang X, Sun AY, Duncan IJ. Shale gas wastewater management under uncertainty. J Environ Manag 2016;165:188–98. http://dx.doi.org/10.1016/j.jenvman.2015.09.038.
[65] Lira-Barragán LF, Ponce-Ortega JM, Guillén-Gosálbez G, El-Halwagi MM. Optimal water management under uncertainty for shale gas production. Ind Eng Chem Res 2016;55:1322–35. http://dx.doi.org/10.1021/acs.iecr.5b02748.
[66] Ahmetović E, Martín M, Grossmann IE. Optimization of energy and water consumption in corn-based ethanol plants. Ind Eng Chem Res 2010;49:7972–82. http://dx.doi.org/10.1021/ie1000955.
[67] Martín M, Ahmetović E, Grossmann IE. Optimization of water consumption in second generation bioethanol plants. Ind Eng Chem Res 2011;50:3705–21. http://dx.doi.org/10.1021/ie101175p.
[68] Baliban RC, Elia JA, Floudas CA. Simultaneous process synthesis, heat, power, and water integration of thermochemical hybrid biomass, coal, and natural gas facilities. Comput Chem Eng 2012;37:297–327. http://dx.doi.org/10.1016/j.compchemeng.2011.10.002.
[69] Bernardi A, Giarola S, Bezzo F. Optimizing the economics and the carbon and water footprints of bioethanol supply chains. Biofuels Bioprod Bioref 2012;6:656–72. http://dx.doi.org/10.1002/bbb.1358.
[70] Bernardi A, Giarola S, Bezzo F. Spatially explicit multiobjective optimization for the strategic design of first and second generation biorefineries including carbon and water footprints. Ind Eng Chem Res 2013;52:7170–80. http://dx.doi.org/10.1021/ie302442j.
[71] Elia JA, Baliban RC, Floudas CA. Nationwide energy supply chain analysis for hybrid feedstock processes with significant CO_2 emissions reduction. AIChE J 2012;58:2142–54. http://dx.doi.org/10.1002/aic.13842.
[72] Guerra OJ, Calderón AJ, Papageorgiou LG, Siirola JJ, Reklaitis GV. An optimization framework for the integration of water management and shale gas supply chain design. Comput Chem Eng 2016;92:230–55. http://dx.doi.org/10.1016/j.compchemeng.2016.03.025.
[73] Conradie AE, Kröger DG. Performance evaluation of dry-cooling systems for power plant applications. Appl Therm Eng 1996;16:219–32. http://dx.doi.org/10.1016/1359-4311(95)00068-2.
[74] Conradie AE, Buys JD, Kröger DG. Performance optimization of dry-cooling systems for power plants through SQP methods. Appl Therm Eng 1998;18:25–45. http://dx.doi.org/10.1016/S1359-4311(97)00020-3.
[75] Williamson N, Behnia M, Armfield SW. Thermal optimization of a natural draft wet cooling tower. Int J Energy Res 2008;32:1349–61. http://dx.doi.org/10.1002/er.1456.
[76] Yang C, Yang Z, Cai R. Analytical method for evaluation of gas turbine inlet air cooling in combined cycle power plant. Appl Energy 2009;86:848–56. http://dx.doi.org/10.1016/j.apenergy.2008.08.019.
[77] De Sa A, Al Zubaidy S. Gas turbine performance at varying ambient temperature. Appl Therm Eng 2011;31:2735–9. http://dx.doi.org/10.1016/j.applthermaleng.2011.04.045.
[78] Salazar JM, Diwekar U, Constantinescu E, Zavala VM. Stochastic optimization approach to water management in cooling-constrained power plants. Appl Energy 2013;112:12–22. http://dx.doi.org/10.1016/j.apenergy.2013.05.077.
[79] Koch H, Vögele S. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. Ecol Econ 2009;68:2031–9. http://dx.doi.org/10.1016/j.ecolecon.2009.02.015.
[80] Koch H, Vögele S, Kaltofen M, Grünewald U. Trends in water demand and water availability for power plants-scenario analyses for the German capital Berlin. Clim Change 2012;110:879–99. http://dx.doi.org/10.1007/s10584-011-0110-0.
[81] Barros MTL, Tsai FT-C, Yang S, Lopes JEG, Yeh WW-G. Optimization of large-scale hydropower system operations. J Water Resour Plan Manag 2003;129:11. http://dx.doi.org/10.1061/(ASCE)0733-9496(2003)129:3(178).
[82] Lehner B, Czisch G, Vassolo S. The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 2005;33:839–55. http://dx.doi.org/10.1016/j.enpol.2003.10.018.
[83] Mo B, Gjelsvik A, Grundt A. Integrated risk management of hydro power scheduling and contract management. IEEE Trans Power Syst 2001;16:216–21. http://dx.doi.org/10.1109/59.918289.
[84] Raje D, Mujumdar PP. Reservoir performance under uncertainty in hydrologic impacts of climate change. Adv Water Resour 2010;33:312–26. http://dx.doi.org/10.1016/j.advwatres.2009.12.008.
[85] van Vliet MTH, Yearsley JR, Ludwig F, Vögele S, Lettenmaier DP, Kabat P. Vulnerability of US and European electricity supply to climate change. Nat Clim Chang 2012;2:676–81. http://dx.doi.org/10.1038/nclimate1546.
[86] Bartos MD, Chester MV. Impacts of climate change on electric power supply in the Western United States. Nat Clim Chang 2015;5:748–52. http://dx.doi.org/10.1038/nclimate2648.
[87] van Vliet MTH, Wiberg D, Leduc S, Riahi K. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nat Clim Chang 2016;6:375–80. http://dx.doi.org/10.1038/nclimate2903.
[88] Koleva MN, Polykarpou EM, Liu S, Styan CA, Papageorgiou LG. Optimal design of water treatment processes. Desalin Water Treat 2016;57:26954–75. http://dx.doi.org/10.1080/19443994.2016.1173595.
[89] Papapostolou C, Kondili E, Kaldellis JK. Development and implementation of an optimisation model for biofuels supply chain. Energy 2011;36:6019–26. http://dx.doi.org/10.1016/j.energy.2011.08.013.
[90] Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD. Impact of Shale Gas Development on Regional Water Quality. Science (80-) 2013;340. http://dx.doi.org/10.1126/science.1235009. [1235009–1235009].
[91] Rahm BG, Bates JT, Bertoia LR, Galford AE, Yoxtheimer DA, Riha SJ. Wastewater management and Marcellus Shale gas development: trends, drivers, and planning implications. J Environ Manag 2013;120:105–13. http://dx.doi.org/10.1016/j.jenvman.2013.02.029.
[92] Olmstead SM, Muehlenbachs LA, Shih J, Chu Z, Krupnick AJ. Shale gas development impacts on surface water quality in Pennsylvania. Proc Natl Acad Sci USA 2013;110:4962–7. http://dx.doi.org/10.1073/pnas.1213871110.
[93] Warner NR, Christie CA, Jackson RB, Vengosh A. Impacts of shale gas wastewater disposal on water quality in western Pennsylvania. Environ Sci Technol 2013;47:11849–57. http://dx.doi.org/10.1021/es402165b.
[94] Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environ Sci Technol 2014;48:8334–48. http://dx.doi.org/10.1021/es405118y.
[95] Rahm BG, Riha SJ. Evolving shale gas management: water resource risks, impacts, and lessons learned. Environ Sci Process Impacts 2014;16:1400. http://dx.doi.org/10.1039/c4em00018h.
[96] Calderón AJ, Guerra OJ, Papageorgiou LG, Siirola JJ, Reklaitis GV. Preliminary evaluation of shale gas reservoirs: appraisal of different well-pad designs via performance metrics. Ind Eng Chem Res 2015;54:10334–49. http://dx.doi.org/10.1021/acs.iecr.5b01590.
[97] Guerra OJ, Calderón AJ, Papageorgiou LG, Gintaras VR. Wastewater quality impact on water management in shale gas supply chain. In: Proceedings 26th eur. symp. comput. aided process eng. – ESCAPE 26, Elsevier Masson SAS; 2016. p. 1371–6. 〈http://dx.doi.org/10.1016/B978-0-444-63428-3.50233-2〉.
[98] Gregory KB, Vidic RD, Dzombak DA. Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements 2011;7:181–6. http://dx.doi.org/10.2113/gselements.7.3.181.
[99] Sobol′ I. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Math Comput Simul 2001;55:271–80. http://dx.doi.org/10.1016/S0378-4754(00)00270-6.

[100] Saltelli A, Tarantola S, Chan KP-S. A quantitative model-independent method for global sensitivity analysis of model output. Technometrics 1999;41:39–56. http://dx.doi.org/10.1080/00401706.1999.10485594.
[101] Foo DCY. State-of-the-art review of pinch analysis techniques for Water network synthesis. Ind Eng Chem Res 2009;48:5125–59. http://dx.doi.org/10.1021/ie801264c.
[102] Jeżowski J. Review of water network design methods with literature annotations. Ind Eng Chem Res 2010;49:4475–516. http://dx.doi.org/10.1021/ie901632w.
[103] Bagajewicz M. A review of recent design procedures for water networks in refineries and process plants. Chem Eng 2000;24:2093–113. [doi:S0098-1354(00)[00579-2].
[104] Kim JK, Smith R. Cooling water system design. Chem Eng Sci 2001;56:3641–58. http://dx.doi.org/10.1016/S0009-2509(01)00091-4.
[105] Kakaras E, Doukelis A, Prelipceanu A, Karellas S. Inlet air cooling methods for gas turbine based power plants. J Eng Gas Turbines Power 2006;128:312. http://dx.doi.org/10.1115/1.2131888.
[106] Gololo KV, Majozi T. On synthesis and optimization of cooling water systems with multiple cooling towers. Ind Eng Chem Res 2011;50:3775–87. http://dx.doi.org/10.1021/ie101395v.
[107] Rubio-Castro E, Serna-González M, Ponce-Ortega JM, El-Halwagi MM. Synthesis of cooling water systems with multiple cooling towers. Appl Therm Eng 2013;50:957–74. http://dx.doi.org/10.1016/j.applthermaleng.2012.06.015.
[108] Jonsson M, Yan J. Humidified gas turbines – a review of proposed and implemented cycles. Energy 2005;30:1013–78. http://dx.doi.org/10.1016/j.energy.2004.08.005.
[109] Al-Ibrahim AM, Varnham A. A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia. Appl Therm Eng 2010;30:1879–88. http://dx.doi.org/10.1016/j.applthermaleng.2010.04.025.
[110] Farzaneh-Gord M, Deymi-Dashtebayaz M. Effect of various inlet air cooling methods on gas turbine performance. Energy 2011;36:1196–205. http://dx.doi.org/10.1016/j.energy.2010.11.027.
[111] Feeley TJ, Skone TJ, Stiegel GJ, McNemar A, Nemeth M, Schimmoller B, et al. Water: a critical resource in the thermoelectric power industry. Energy 2008;33:1–11. http://dx.doi.org/10.1016/j.energy.2007.08.007.
[112] DeNooyer TA, Peschel JM, Zhang Z, Stillwell AS. Integrating water resources and power generation: the energy–water nexus in Illinois. Appl Energy 2016;162:363–71. http://dx.doi.org/10.1016/j.apenergy.2015.10.071.
[113] Guerra OJ, Tejada DA, Reklaitis GV. An optimization framework for the integrated planning of generation and transmission expansion in interconnected power systems. Appl Energy 2016;170:1–21. http://dx.doi.org/10.1016/j.apenergy.2016.02.014.
[114] Bazmi AA, Zahedi G. Sustainable energy systems: role of optimization modeling techniques in power generation and supply – a review. Renew Sustain Energy Rev 2011;15:3480–500. http://dx.doi.org/10.1016/j.rser.2011.05.003.
[115] Bromham L, Dinnage R, Hua X. Interdisciplinary research has consistently lower funding success. Nature 2016;534:684–7. http://dx.doi.org/10.1038/nature18315.